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USE OF RADIOACTIVE TRACERS TO DETECT CRACKING IN THE WELD METAL OF STEEL STRUCTURAL WELDS IN SEAWATER

by
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T-3150

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ABSTRACT

A novel non-destructive testing method for detecting cracks in the weld metal of structural steel welds in offshore platforms has been investigated. A radioactive tracer is included in the interior passes of a multiple pass weldment, but not in the outer cap or root passes. When a crack penetrates into this tracer-laden region, corrosion inside the crack will release the tracer to the environment. Although this study was done with chemical tracers, it is proposed that radioactive tracers be used for this process because of the higher sensitivity of radiation detection methods. Based on the chemical tracer work of this study, it appears that the process is a viable means of detecting cracks in the weld metal.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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INTRODUCTION

1.0 PURPOSE

The purpose of this thesis is to evaluate the technical feasibility of a non-destructive technique proposed for inspection of the weld metal of welds in offshore structures. With the proposed technology, a radiation detector would be capable of detecting the presence of corrosion in exposed cracks that penetrate beyond a predetermined critical depth and, thus, warrant repair.

During fabrication, a radioactive tracer is to be included in the interior passes of a multiple pass weldment, but not in the outer cap and root passes. When a stress-corrosion or corrosion fatigue crack penetrates through these outer passes and into the tracer-laden interior passes, the tracer will be released into the adjoining seawater environment, setting off the detector and giving an indication. (See Figure 1.)

The foreseen advantages of this non-destructive testing method are its reliability, speed, ease of automation, and insensitivity to marine fouling on the surface of the structure. Reliability of offshore inspection techniques is particularly important, given the

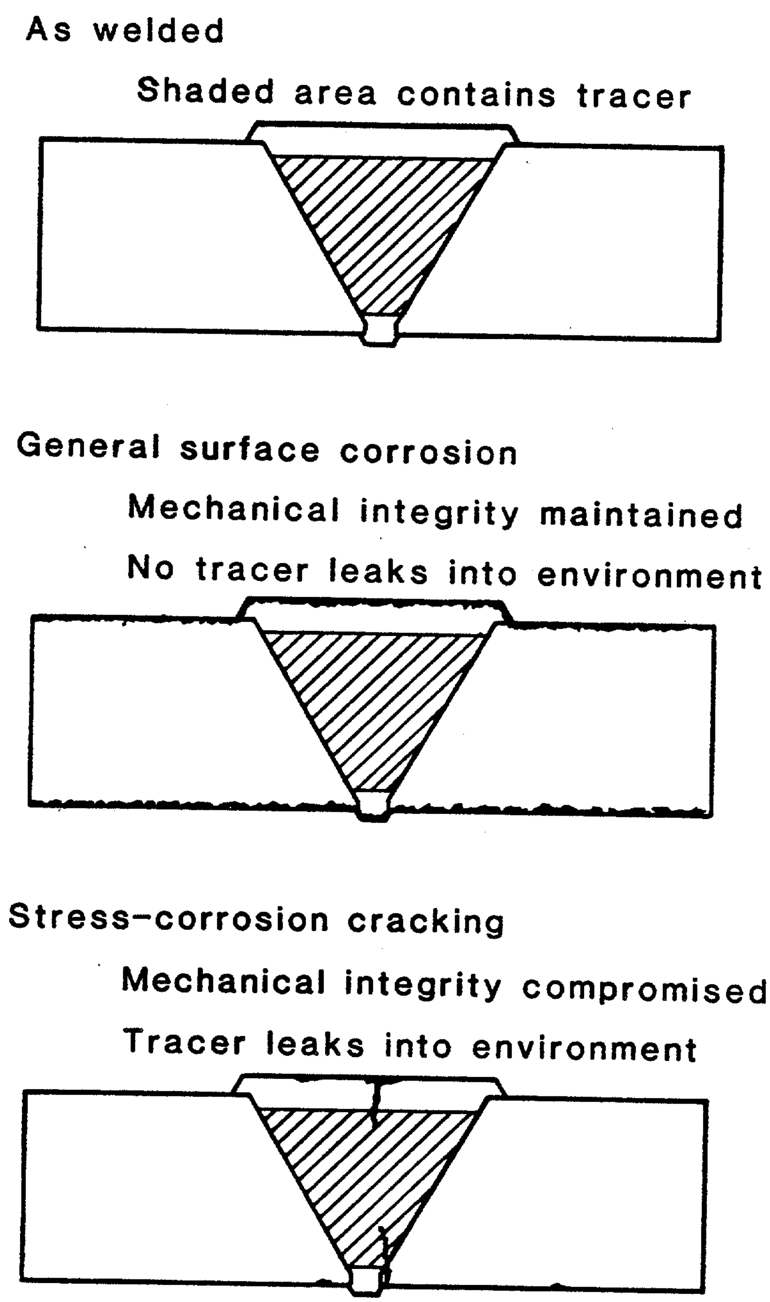

Figure 1: General Concept of NDE Method

extreme expense of unnecessary repair and the potentially tragic consequences of undetected flaws. Speed is critical because operating expenses for offshore work are substantial. Given that typically 49 support people are necessary for a single working diver(1) and the myriad of problems associated with deep dives(2), any system that can be easily automated will result in obvious and substantial cost savings. Automation is already being used to offset the high costs and poor efficiency of offshore inspection. Remote operated vehicles (ROVs) for offshore use have been developed and are currently being used to visually inspect structures(3). These should prove relatively easy to adapt to the proposed inspection technique. In addition, because this method is insensitive to marine growth on the surface of the structure, it will not require the extensive cleaning that consumes the greatest portion of inspection time(4).

The foreseen disadvantages of this system are associated with the containment of radiation released by the tracer during fabrication, welding, and weld repair. The detrimental effects of radiation on health are well known and should be minimized whereever possible. For this reason, special attention should be given to welding and weld repair, where small particles of radioactive material may be released into the atmosphere as welding fume or grinding slag.

Tracer released by the corrosion-assisted cracking of the structure will be contained in a stagnant boundary layer constrained by the marine growth on the surface. Marine growth is common on offshore platfroms in a wide variety of geographical locations(5,6,7), with the Cook Inlet, Alaska area as the sole apparent exception(8). This marine growth should limit lateral motion of the seawater immediately adjacent to the platform members, creating a stagnant boundary layer. Even assuming that any tracer escaping from a stress-corrosion crack is immediately diluted to an undetectably low concentration when it reaches the open ocean, diffusion through this stagnant boundary layer will require both a concentration gradient and a substantially larger concentration adjacent to the crack opening. Radiation from this contained tracer will then be detected by the scanning inspection system.

2.0 REVIEW OF CURRENT OFFSHORE PLATFORM INSPECTION METHODS

Inspection techniques currently used on offshore structures include primarily visual inspections, often accompanied by magnetic particle and ultrasonic inspections and electrical measurements to assess the status of the cathodic protection system(9). Vibrational analyses(10) and eddy current testing(11) are also sometimes used. Acoustic emission systems have been proposed and tested for inspection of the K-joints used in offshore platforms(12) and have been field tested(13), but do not seem to be used commercially yet.

Visual inspections usually require the presence of divers to clean and inspect the platform. Because of the expense involved in removing marine fouling from the surface of offshore platforms, it is common practice to only thoroughly inspect those portions of the structure considered most critical--the node welds. Visual inspections suffer from relatively poor sensitivity with one operator noting that "cracks 500mm (20 inches) long (were) missed by trained inspection divers"(4). For this reason, visual inspection is usually accompanied by magnetic particle inspection for crack detection and ultrasonic inspection for sizing of cracks found with the magnetic particle inspection(9). Visual inspection alone is usually limited to an occaisional cursory inspection to determine the presence and overall mechanical integrity of braces, and the presence of sacrificial anodes.

Although magnetic particle inspection requires an extremely thorough and expensive cleaning of all marine growth from the surface of the platform, is time consuming, and only provides the surface character of detected flaws, it appears to be the non-destructive testing method most commonly used to enhance visual inspection(14).

Ultrasonic inspection of offshore platforms, even when aided by the use of transducer arrays and acoustic holography techniques, requires a great deal of expensive diver time(15) except in those limited cases where it can be automated(16,17). Although some inspection firms maintain that ultrasonic testing "proceeded(sic) by careful visual inspection, can establish a known quality of welds at a reasonable relative cost"(18), it is considered very unreliable by some platform operators because of the high level of operator skill and interpretation required(13). Although ultrasonic inspection is approved by AWS D1.1-85 for inspection of the tubular joints typical of offshore platforms, this specification is not written for in-service inspection. For example, seawater is not listed as an acceptable couplant. Ultrasonic inspection offshore is further complicated by the effects of corrosion. Corrosion pits, most common on those structures for which inspection is most critical, can give false backwall echoes when thickness gaging, virtually eliminate useful sound entry when using the angle beam inspection methods suggested by

AWS D1.1-85 for inspection of tubular structures, and reflect shear waves in such a manner as to give false indications(19). The difficulties associated with communication between the diver, who is handling the transducer, and the technician on the surface who has access to the oscilloscope readout can be reduced through the use of some specialized systems(20), although the problems associated with the very long lengths of cable required for deep structures remain substantial. The lack of a permanent record and some problems associated with the complexity of fillet welds may also be reduced somewhat by the use of specialized systems(21,22).

Vibrational analyses, which analyze the dynamic response of the structure or individual members of the structure to natural wave- and wind-induced vibrations or artificially induced vibrations, have been proposed and are commercially available(10). Although most of these analyses only claim to be able to detect complete severance of structurally important members(23,24), one laboratory analysis claims that forced vibration analyses are capable of detecting cracks whose length are as small as 38 percent of the circumference of a tubular member(25). Field tests of forced vibration analyses do suggest that they are better able to determine modal characteristics of the vibrations. The advantages of vibration analysis systems are that they are easily applied and are relatively inexpensive. The primary disadvantages of these systems are their poor sensitivity to cracks that do not completely sever a structurally important member and sensitivity to other factors, such as changes in mud line, soil properties(26), movement of fluid in liquid storage tanks, changes in deck weight, and the weight of marine growth(27).

Eddy current systems are commercially available, but are new to the offshore industry and do not appear to have wide commercial acceptance. Although the specialized systems developed for inspection of North Sea platforms do not appear to require the thorough cleaning required of other NDT systems, their ability to assertain the depth of cracks is limited(11).

Acoustic emission systems have been proposed and tested on the tubular K-joints used in offshore oil platforms, with some success(12). Field tests on a small platform also had promising results with far fewer transducers per joint, but the number of transducers will have to be increased dramatically in order to monitor larger, more complex platforms. The primary disadvantage of acoustic emission systems is the very large number of transducers and amount of wiring needed to monitor an offshore oil platform. Problems with noise from equipment and breaking waves have been overcome in field tests(13).

Internal friction damping methods have been investigated as a means of testing the wire(28) and synthetic(29) ropes used as mooring lines with some success. However, field tests will be required before this method can be considered able to accurately assess the condition of mooring lines.

Radioactive tracers have been used successfully to test pile groutings(30,31) and have been suggested for inspection of reinforced concrete platforms. The latter would be accomplished by analyzing the seawater for radioactive corrosion products released by corrosion of the tracer-laden re-inforcing steel exposed to the seawater by cracking of the concrete(32).

3.0 CURRENT INSPECTION GUIDELINES

In the United Kingdom waters of the North Sea, inspections are required by United Kingdom Offshore Installations (Construction and Survey) Regulations 1974, Statutory Instrument 289 and, in response to these regulations, Certificates of Fitness are issued, primarily by Lloyds Register and Det norske Veritas (4). In American waters, the inspection of offshore platforms is currently being regulated, on a limited basis, by API(33) and ABS(34,35). Even so, in the U. S. coastal waters there is still very little "codified guidance concerning procedures, documentation, and qualification of inspection systems or personnel"(13). Although the level of inspection of U. S. platforms is increasing, as recently as 1980 most owners limited their inspection efforts to "an occaisional underwater visual inspection to detect major damage"(9). API specification RP 2A, however, does recommend a visual inspection yearly and a more detailed inspection every five years(9).

4.0 FAILURE OF OFFSHORE PLATFORMS, CASE HISTORIES

A visual inspection of the Ranger I jack-up platform apparently failed to detect any major cracks in the main structural members of the platform shortly before it collapsed May 10, 1979, off the coast of Galveston, Texas(9). Subsequent analysis of the wreckage indicated that the failure initiated at a 575mm (23 inch) corrosion fatigue crack that grew over the life of the structure in one of the legs of the platform(36).

The offshore platform Alexander L. Kielland capsized and sank when one of its five legs separated from the rest of the structure on March 27, 1980 in the Ekofisk area of the North Sea. Only 89 of the 212 people on board were rescued. The original fatigue fracture initiated at a fillet weld joining a hydrophone to a non-redundant brace. Final fracture occurred in 6-10 meter seas and covered only the final one-third of the circumference(37).

5.0 CORROSION-RELATED FAILURE MECHANISMS OF OFFSHORE PLATFORMS

Corrosion-related failures of offshore platforms are frequently a result of corrosion fatigue(38). Corrosion fatigue is a form of metal fatigue where the fatigue life is greatly reduced by exposure to a corrosive environment. In the marine environment, initiation of a fatigue crack in an unprotected steel is fairly rapid(39) and crack propagation rates are as high as ten times those of the same steel stressed equally in air(40). Freely corroding steel in seawater does not exhibit an endurance limit(41).

However, cathodic protection can restore the fatigue life of a member to approximately what it would be in air(42). Cathodic protection apparently delays the initiation of a fatigue crack sufficiently that it more than compensates for the enhanced growth rate of corrosion fatigue cracks in cathodically protected steel(40).

Dissolved oxygen also plays a significant role in corrosion fatigue of structural steel in seawater, with de-aerated solutions exhibiting a fatigue life and endurance limit equivalent to that of the same steel in air(41). Weld defects, particularly undercuts, dramatically reduce the fatigue life of offshore structures, often completely offsetting the initiation resistance inparted to the steel by cathodic protection(43). Jaske, et al, have done a fairly thorough review of corrosion fatigue of structural steels in seawater for application in offshore structures(44).

Stress-corrosion is a mechanism by which a sub-critical flaw in a susceptible material may propagate under a static load when exposed to an appropriate environment. Cathodic protection of high strength steels in seawater is not necessarily effective in preventing environmentally enhanced cracking. If the potential is made even slightly more negative(cathodic) than optimum, environmentally enhanced cracking will propagate by a hydrogen embrittlement mechanism. If the potential is slightly more positive than the optimum range, stress-corrosion cracking will propagate the crack. Complicating this situation is the fact that the potential of a cathodically protected offshore platform varies slightly with position and the optimum potential varies with oxygen content(45,46), which is a function of depth and time of year(47) in an oceanic environment. At typical potentials for cathodic protection, environmentally enhanced cracking usually will not occur in an aerated chloride solution, but may occur in a de-aerated solution(45). This will prove most damaging in the deepest parts of structures, where oxygen levels are at their lowest(47) and inspection is most difficult. In addition, cathodic protection has very little effect on stress-corrosion crack propagation rates, particularly after the cracks have penetrated beyond a very shallow depth(48). This is most significant for platforms that use impressed current systems, as a temporary power loss could allow a stress-corrosion crack to develop and propagate to the point that cathodic protection would be unable to stop it.

Although one author has identified stress-corrosion cracking a one of the common failure mechanisms of offshore structural components(14), there are few, if any, documented cases of structural failures that can be directly attributed to stress-corrosion cracking. This is consistent with the observation that carbon steels are generally not very susceptible to stress-corrosion cracking in chloride solutions when their ultimate strength is less than 145 ksi (1000Mpa)(48), much greater than the strength of the low-carbon steels typically used in offshore platforms(49). In the few published cases where high strength steels have been introduced into offshore platforms, the resistance of the proposed steel to stress-corrosion cracking has been established prior to use, although the effect of the oxygen content on this susceptibility has not been published(50). For these reasons, stress-corrosion cracking is not considered a problem in offshore platforms(51).

6.0 FRACTURE SENSITIVITY AND ALLOWABLE DEFECT SIZES

The sensitivity of offshore structures to defects is difficult to assess. Because of the high redundancy of these structures, complete severance of most individual members can be tolerated. Even in failures like those of Ranger I(36) and the Alexander L. Kielland(37), the size of the critical crack lengths in the non-redundant members was significant, twenty-three inches in one and two-thirds of the circumference of the critical brace in the other. Because of load-sharing among members, it is difficult to establish when a crack reaches a critical size. As a crack grows in a node, that joint becomes more compliant, distributing its share of the load among other members of the structure and quite possibly reducing the stress intensity on the crack sufficiently that the crack is arrested.

Even so, there is a need for improved inspection methods capable of detecting less than through-thickness cracks. As confidence in design criteria improve, the redundancy designed into offshore structures is decreasing and inspection methods must keep pace. If inspection methods do not improve and the ability of the structures to tolerate completely severed members is reduced, the results could prove disastrous, as was the case in the Alexander L. Kielland (52).

7.0 RADIOACTIVE TRACER STUDIES

Radioactive tracers have been used to detect and measure corrosion for many years. In the oilfield, they have been used to measure the effect of inhibitors on general corrosion rates(53) and to monitor the placement of grout in offshore platform groutings(30,31). In a study of the effect of inhibitors on the corrosion of downhole casings, a small amount of Co-60 was included in an section of J-55 casing and the tracer released by corrosion of this section was measured downstream using radioactive detection methods. This provided a highly sensitive measure of the fairly low corrosion rates in the inhibited effluents over a long period of time(53). Offshore, a number of isotopes have been included in the grout used to fill the connections between the base of a platform and piles driven into the sea floor. Radiation detectors were then able to accurately determine when the cavity was completely filled(30,31).

8.0 SELECTION OF A RADIOACTIVE TRACER AND DETECTION SYSTEM

The radioisotope chosen as a tracer for this process must be readily alloyable in steel weld metals, be soluble in seawater, emit beta-radiation, and have a sufficiently long half-life that it lasts long enough to provide a useful in-service inspection technique. If an isotope is not soluble in seawater, it may not escape the stress-corrosion crack to set off the detector. Radiation from alpha-emitting isotopes will not penetrate seawater enough to set off a detector more than a very short distance away. On the other hand, gamma radiation penetrates steel so well that the outer layer of weld passes will not provide enough shielding to absorb radiation emitted by tracer contained in the interior passes. These criteria, when combined with the requirement that the isotope not be normally present in seawater, limit the potential isotopes to cobalt-60 and nickel-63(54,55). See Figure 2 for a comparison of the half-life of these two isotopes to the typical twenty to thirty year design life of an offshore platform.

The radiation detection system chosen for the detection of this tracer must be capable of detecting its radiation, portable, and compatible with the corrosive conditions and range of pressures encountered by offshore structures. Ion-collection devices like ionization chambers, proportional counters and Geiger-Mueller counters all require that the radiation emitted by the radioisotope pass through a "window" and ionize a gas inside the detector. Since the window itself will absorb radiation, the maximum allowable thickness of the window is a function of the penetrating ability or energy of the impinging radiation, and ion collection devices capable of detecting relatively low-energy beta emissions like those of Co-60 and Ni-63 require especially thin and correspondingly delicate windows(56). Because these thin windows cannot withstand the high pressures encountered at depth and changes in internal pressure to compensate for external pressure changes will have radical effects on the performance of the detector, ion-collection devices are not

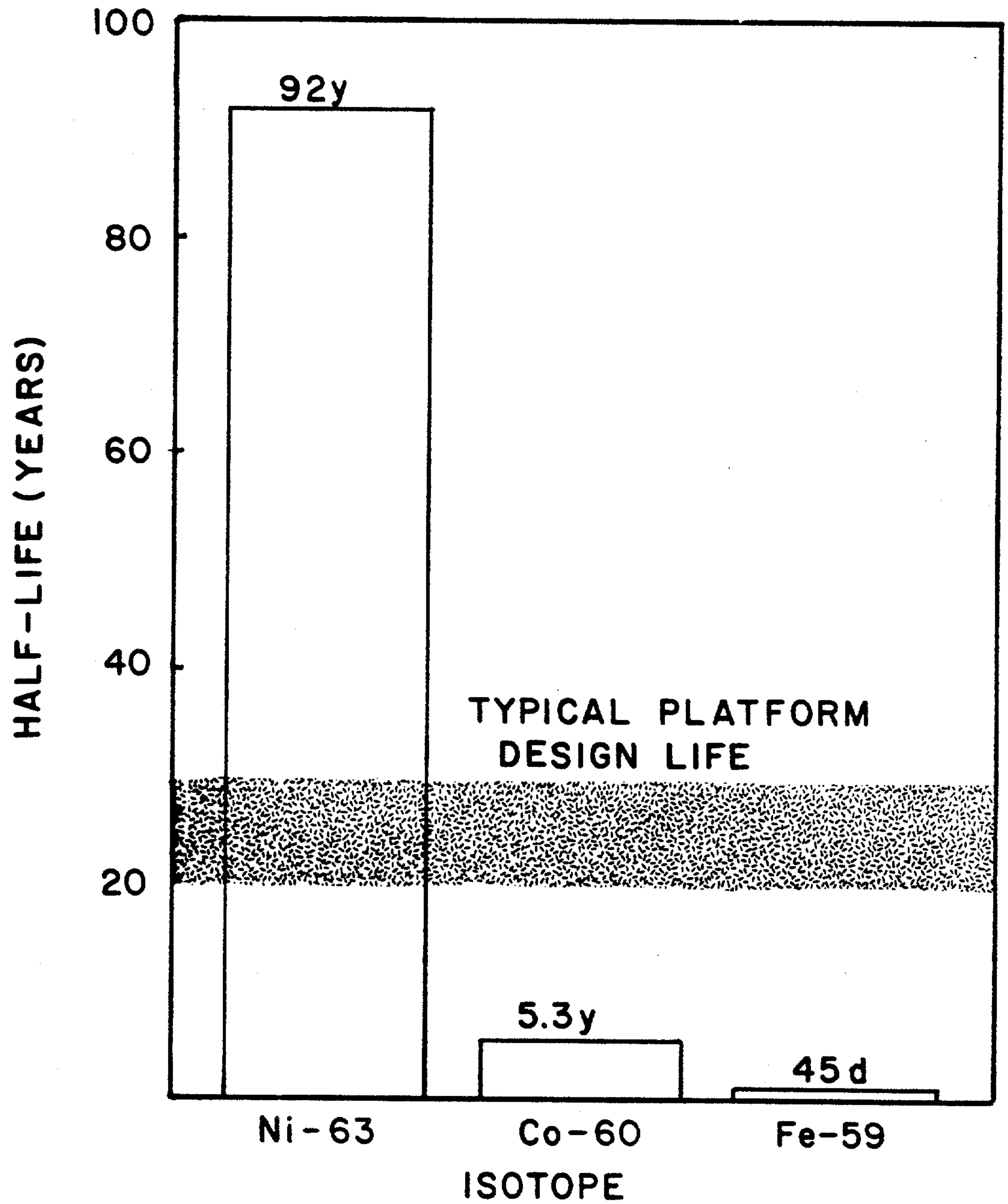

FIGURE 2: HALF-LIVES OF THREE BETA RADIATION EMITTING ISOTOPES

suitable for this application.

Scintillation detectors, on the other hand, seem to be ideal. They are not sensitive to changes in pressure and are capable of detecting low energy beta emissions(57). Scintillator materials used for detection of beta-radiation include anthracene, naphthalene with small amounts of anthracene, two or three other, less suitable organic materials, also based on a benzene ring structure(58), europium-activated calcium fluoride(59), and a variety of lithium silicate glasses(60). Although europium-activated calcium fluoride scintillating crystals have successfully been used to detect low-energy beta emissions in gaseous environments, there were significant difficulties with the absorption of water(57) that preclude the use of this type of scintillator in this application. The plastics will probably prove unacceptable because the absorption of tritiated water will lead to increased background noise and decreased sensitivity(61). For these reasons, a cerium-activated lithium silicate glass will probably prove to be the optimum scintillator in spite of its slightly less energetic response(59).

EXPERIMENTAL PROCEDURE

1.0 PURPOSE

The purpose of the experimental work of this thesis was to establish that corrosion of cracks in ferrous alloy welds containing the selected tracers will release those trace elements into the seawater environment to which the alloys are exposed. Secondly, quantitatively measure that release, and then estimate the level of radioactive tracer needed in the final application.

2.0 TEST FACILITY AND EQUIPMENT

All chemical analyses of the tracer content of the artificial seawater solutions used in this research were analyzed on a Perkin-Elmer Model 306 Atomic Absorption Spectrophotometer. Cobalt was analyzed using the 240.7 nm spectral line and nickel was analyzed using the 232.0 nm line.

Mechanical testing and fatigue precracking were done on an MTS Model 810 Material Test System. On one side of the notch in the specimen, the load was transmitted through a standard grip as specified in ASTM E399 and, on the other side, through the threaded bolt hole shown in Fig. 2.

Corrosion tests were run in specially made plastic

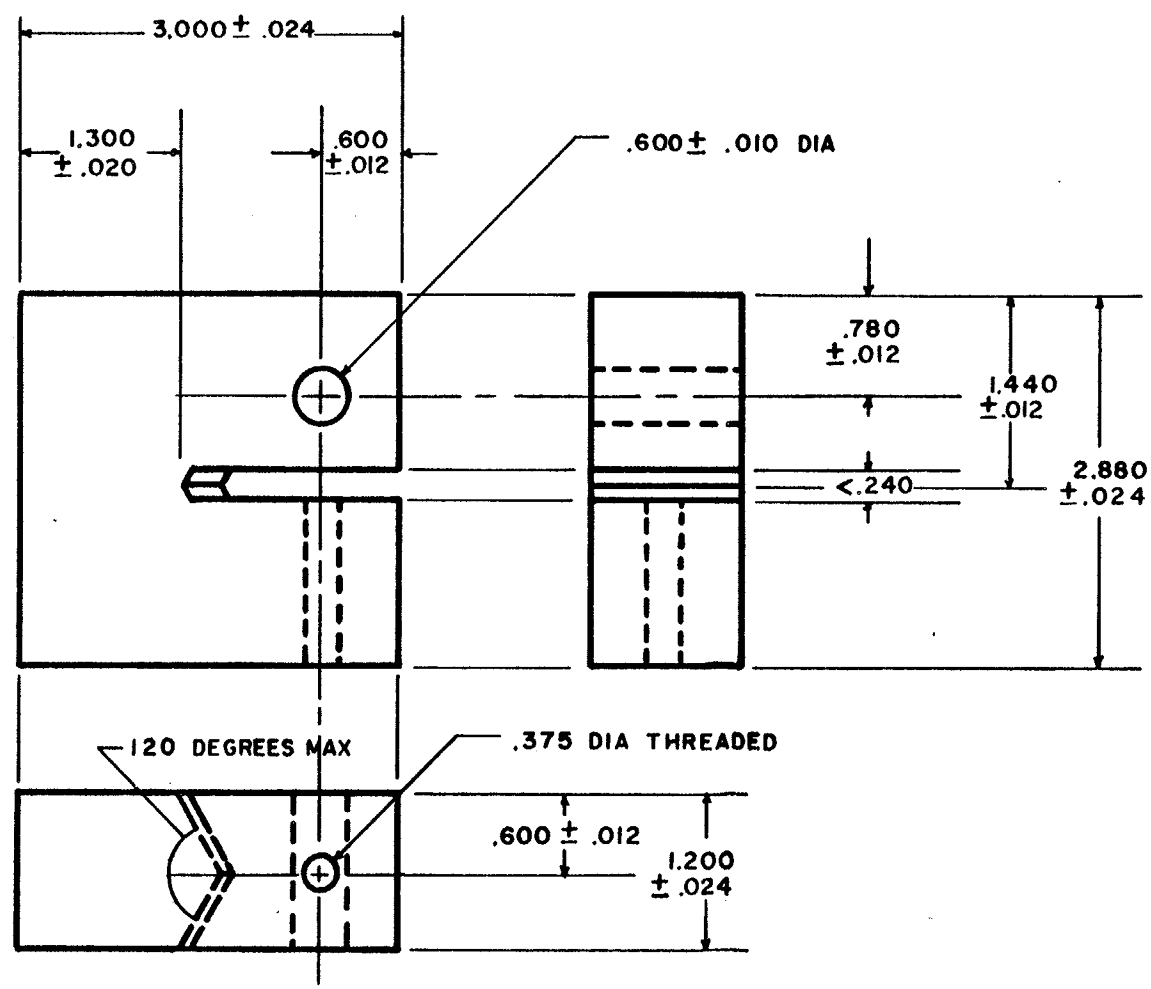

FIGURE 3: MODIFIED ASTM E399 FRACTURE SPECIMEN

baths that were designed so as to minimize the amount of solution and, thus, maximize the concentration of tracer. The specimens that were tested in a stagnant bath required approximately 100ml and the specimens tested in stirred baths required about 175ml of artificial seawater. The difference between the two was due to the need for space for a magnetic stirring rod below the specimen in the solution.

All welding was done on welding equipment donated by Hobart Bros. Co. A Hobart Model RC500 power supply was used with a Hobart Model AI-22 GMAW Controller on a Hobart Model 1044 track drive. Welding was done in the flat position with an industrial purity argon shield gas.

3.0 PREPARATION OF ARTIFICIAL SEAWATER SOLUTIONS

All artificial seawater solutions were prepared in accordance with ASTM D-1141 (see Appendix A).

4.0 TEST MATERIALS

The weld metals chosen for stress-corrosion cracking tests were Multimet 155, a iron-nickel superalloy, and 18Ni(250) maraging steel. These were selected on the basis of their nickel and cobalt contents. (Because of the poor sensitivity of atomic absorption methods relative to radioactive detection methods, it was necessary to use filler metals with considerably greater concentrations of cobalt and nickel than will be considered appropriate for the final application of this process.) 18Ni(250) maraging steel is a very high strength precipitation strengthened martensitic steel. Multimet 155 is an austenitic iron-nickel superalloy. The compositions of these alloys are given in Table I.

5.0 ISOTOPE EVALUATIONS--GENERAL CORROSION IN SEAWATER

Bead-on-plate SAW welds were performed on a low-carbon steel plate covered with a metal powder of a stable isotope of the proposed tracer elements, nickel, cobalt, and titanium. For the elements cobalt and nickel, pure metal powders were used. For titanium, a pure metal powder was not available and a Ti-6%Al-4%V powder was used. A shallow 3mm (1/8") V-groove was cut into the plate, filled with metal powder, and a weld bead was produced in the powder-filled groove. The wire used was a plain carbon E70S-3 wire and a standard commercial flux was used. The welding parameters were chosen so as to minimize dilution and thus maximize the concentration of the tracer element in the weld metal.

Drill shavings of the weldments were removed and

TABLE I

Composition of Alloys
Used in Crack Corrosion Tests

Alloy	Element (wt. %) Co	Ni	Other
18Ni(250)	7.50	18.50	4.8Mo, 0.42Ti, 0.003B, 0.10Al, 0.03C, bal. Fe
Multimet 155	19.83	20.15	21.82Cr, 3.4Mo, 1.19Nb+Ta, 2.65W, 0.60C, 1.47Mn, 0.15N, bal. Fe

placed in measured amounts of artificial seawater (ASTM D-1141), which was then periodically analyzed with atomic absorption methods for the presence of the tracer element as a soluble corrosion product.

6.0 ISOTOPE EVALUATIONS--IN-SITU IRRADIATION

Samples of the weld metals tested (see Table I for alloys and compositions) were subjected to a high intensity neutron flux (approximately 10^{13} neutrons/cm^2-s) for one hour in a nuclear reactor and analyzed for the presence of gamma radiation emitting isotopes with gamma ray spectroscopy. This test was performed by Los Alamos National Laboratory.

7.0 CRACK CORROSION TESTS

When the tracers considered appropriate for this preliminary investigation using atomic absorption methods of detection were identified, wedge-opening load (WOL) compact tension specimens (see Fig. 2) were constructed from weldments of two alloys containing the tracers in varying amounts. The WOL-CT specimens were fatigue pre-cracked, bolt loaded, painted, and placed in a measured amount of artificial seawater which was then periodically monitored for the presence of the tracer elements as soluble corrosion products. The specimens were painted so that the corrosion would be confined to the interior of the crack. The level of seawater in the bath was marked and distilled water was added daily to compensate for evaporation. Upon completion of a test, each specimen was fatigue loaded and finally fractured. The fracture surface was then examined in order to quantitatively assess the presence and extent of corrosion in the crack.

RESULTS AND DISCUSSION

1.0 ISOTOPE EVALUATIONS--GENERAL CORROSION IN SEAWATER

The tests described in Section 5.0 of the Experimental Procedures section of this thesis established that cobalt and nickel are released into seawater as soluble corrosion products of steel welds containing those elements as tracers (See Figures 3 and 4). This point is critical to the final application of this process because if these elements formed only insoluble corrosion products, any radioactive tracer released by corrosion of the interior of a crack could not escape the crack and, thereby, allow detection of the crack. Titanium was ruled out as a possible tracer for this initial study using chemical detection methods because other elements in the artificial seawater matrix produced noise in the atomic absorption signal and prevented measurement of titanium concentrations in the range expected in this study (<5ppm).

2.0 ISOTOPE EVALUATIONS--IN-SITU IRRADIATION

The tests described in Section 6.0 of the Experimental Procedure of this thesis were performed in order to determine the feasibility of producing welds with a non-radioactive isotope of the tracer element chosen and

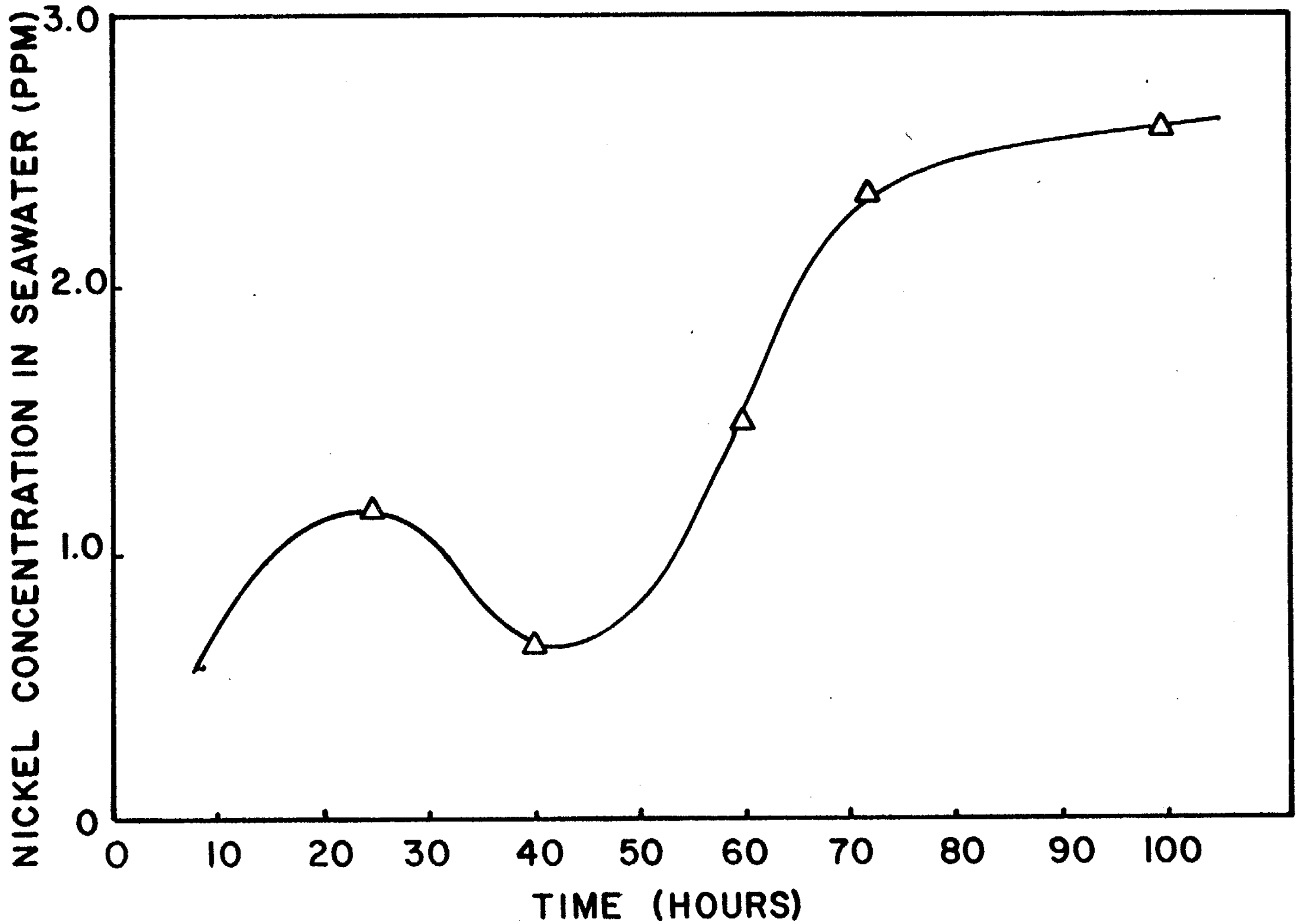

FIGURE 4: CORROSION OF NICKEL WELD SHAVINGS IN ARTIFICIAL SEAWATER

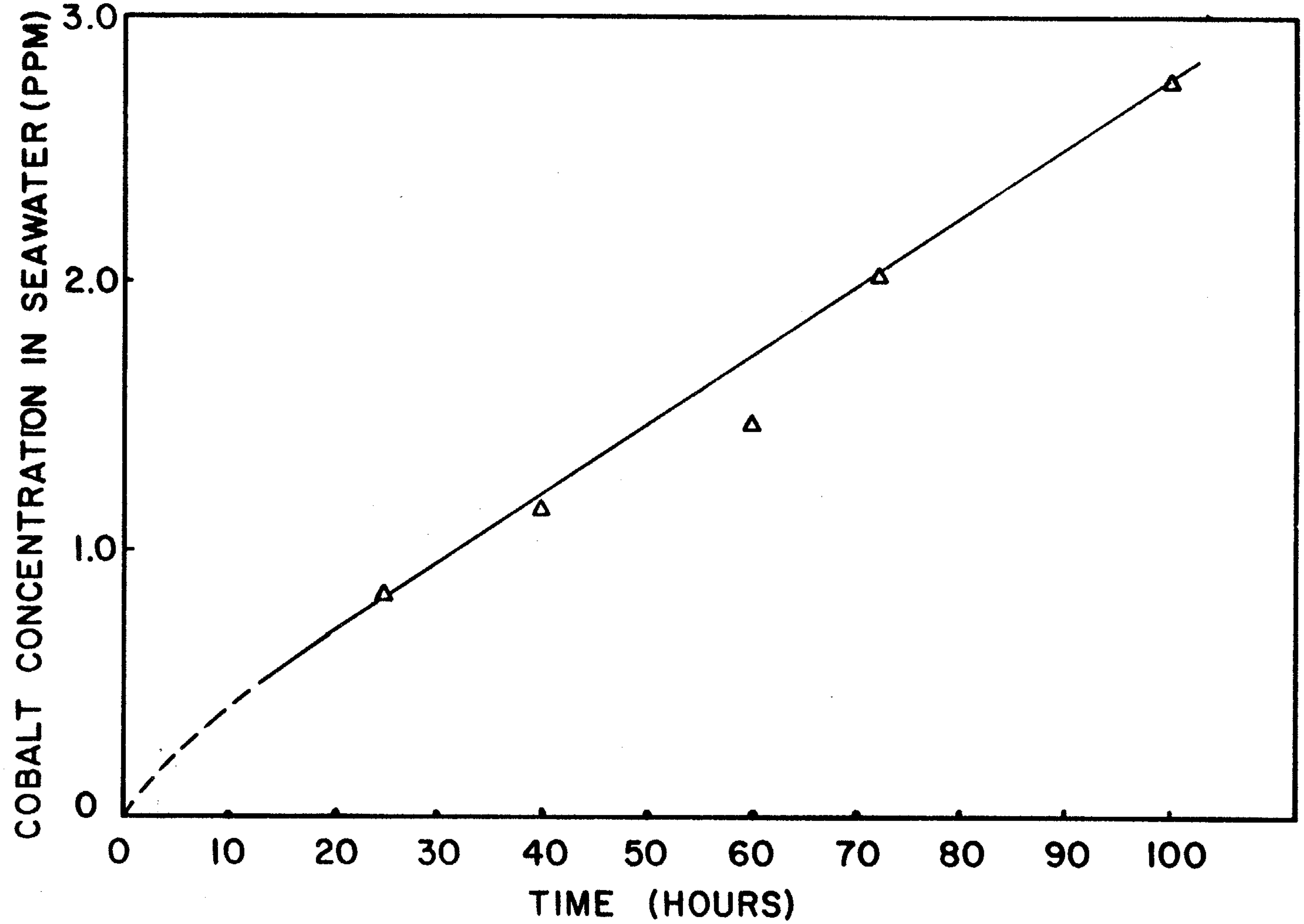

FIGURE 5: CORROSION OF 8% COBALT SHAVINGS IN ARTIFICIAL SEAWATER

then subjecting the weld to a neutron flux in order to transform the element to the desired radioisotope tracer. Relative to a system that requires welding with a radioactive filler metal, the advantages of such a procedure are as follows: 1) it eliminates welder exposure to radiation from welding fumes, welding slag, and the weld bead, 2) it eliminates problems with containment of radioactive grinding slag produced during weld repair, and 3) it dramatically reduces the problems associated with handling and containment of radioactive material before and during fabrication.

As expected, these tests indicated that non-radioactive cobalt transforms readily to Co-60, the desired radioactive isotope of cobalt (See Table II). They also indicated that there may be serious problems associated with the formation of Fe-59, a radioactive isotope of iron that also emits beta radiation. This beta radiation will increase the noise level that the detector receives as it approaches the weld and could mask the radiation from the tracer entirely. However, if a sufficient period of time is allowed to elapse before the first inspection, radioactive decay will eliminate most of the Fe-59 (half-life = 45.1 days) and if the detector is made energy-specific so that it detects only beta-radiation

TABLE II

Results of Irradiation Tests

Isotope	Relative Concentration* in 18Ni(250)	Relative Concentration* in Multimet 155
Co-60	6.4	17.1
Ni-65**	19.0	18.0
Fe-59	71.0	27.0
Cr-51**	0.2	19.7

* Expressed as a percentage of all radioactive isotopes detected

**These and all other isotopes detected either have short half lives(<72 hours) or do not emit beta radiation.

from the desired isotope any problems resulting form the beta emissions of Fe-59 will be virtually eliminated. The output of a scintillation detector can be electronically gated so that only signals from beta emissions of a specific energy or energy range are detected.

Since these tests use gamma ray spectroscopy to measure the presence of radioactive isotopes, they are incapable of detecting isotopes whose decay does not involve the release of gamma rays. Ni-63 is such an isotope and these tests were, therefore, not capable of directly measuring the ability of a neutron flux to transform non-radioactive isotopes of nickel to Ni-63. However, these tests may be capable of indirectly indicating the presence of N-63. The probability of an atom absorbing a neutron and transforming to another isotope is a function of its thermal neutron capture cross-section--the larger the thermal neutron cross section of a given isotope, the more readily it transforms. Ni-65 is formed by the capture of a single neutron by Ni-64 and Ni-63 is formed by the capture of a single neutron by Ni-62. Ni-64 has a natural abundance of 0.9 percent (ie., 0.9% of the stable nickel atoms in nature are Ni-64) and a thermal neutron capture cross-section of 1.5b. Ni-62, on the other hand, has a greater natural abundance of 3.6

percent and a larger thermal neutron capture cross-section of 15b(62). Therefore, the concentration of Ni-63 formed should be much higher than the corresponding concentration of Ni-65, and, since Ni-65 was shown to be present in appreciable concentrations, it is reasonable to assume that Ni-63 was also present. (See Table III for properties of the isotopes discussed.)

3.0 CRACK CORROSION TESTS

These tests established that corrosion of a crack in a ferrous weld metal containing cobalt and nickel will release both those elements into the seawater environment to which the crack is exposed (See Table IV). The type of corrosion that occured in the crack was not conclusively established and is not particularly significant to the final application of this process. Any corrosive process that releases the tracer into the seawater in a soluble form will serve the desired purpose.

4.0 OTHER CONSIDERATIONS

There are several other factors that must be considered before this method can be recommended for actual use. These include radiation safety, environmental and regulatory requirements, salvage costs, effects of cathodic

Table IIIa

Properties of Radioactive Isotopes

Isotope	Half-life	Radiation Type	Energy(MeV)
Co-60	5.26y	beta gamma	0.312 1.33, 1.173
Ni-63	92y	beta	0.067
Fe-59	45.1d	beta gamma	0.46,0.27,1.56 1.10,1.29
Ni-65	2.5h	beta gamma	2.12,0.66,1.02 1.11, 0.37

Table IIIb

Properties of Stable Isotopes

Isotope	Natural Abundance	Thermal Neutron Capture Cross-Section
Co-59	100%	17 ± 2b
Ni-62	3.6%	15 ± 2b
Ni-64	0.9%	1.5 ± 0.2b
Fe-58	0.3%	1.2 ± 0.05b

TABLE IV

TRACER RELEASE FROM CRACK CORROSION TESTS

Alloy	Tracer	Tracer Released (mg/cm^2-hr)
Multimet 155	Co	7.9×10^{-4}
	Ni	1.5×10^{-3}
18Ni(250)	Co	7.0×10^{-5}
	Ni	7.3×10^{-5}

protection, availability of the tracer isotopes, dilution of the tracer as it exits the crack, and sensitivity to the primary modes of failure of the structural members being inspected.

4.1 SAFETY

Safety is always a relevant concern when dealing with radioactive materials. In the proposed system, exposure to radiation will occur in three primary areas--during welding and weld repair, general exposure from the handling of radioactive filler metals and working around a radioactive structure during fabrication, and exposure of workers on the platform during operation. The first two of these may be virtually eliminated by an in-situ irradiation procedure where the tracer element is not made radioactive until all welding has been completed, the welds have passed inspection, and the platform is ready to be towed to its desired location. Exposure to radiation could be eliminated almost entirely if an in-situ irradiation procedure is used with Ni-63 as the intended tracer. Ni-63 only emits a low energy beta emission that will be absorbed completely in less than an inch of water or one-eighth of an inch of steel--ie., the outer weld passes of the weldment. If, however, Co-60 is chosen as the tracer, provisions will have to be made for containment of its highly penetrating gamma radiation, although the outer weld passes will still contain the beta emissions. All exposure will be reduced, of course, by minimizing the radioactive tracer concentration in the weldment.

4.2 ENVIRONMENTAL AND REGULATORY CONCERNS

Title 10, Chapter 1, Part 20 of the Federal Register covers permissable doses, levels and concentrations of radioactive materials, precautionary procedures, record-keeping procedures, and waste disposal. Paragraph 302b of the Federal Register, Title 10, Chapter 1, Part 20, states that,

> "The (Nuclear Regulatory) Commission will not approve any application for a license for disposal of licensed material at sea unless the applicant shows that sea disposal offers less harm to men or the environment than other practical alternative methods of disposal.(63)"

The approval of the Nuclear Regulatory Commission will therefore be needed before radioactive materials can be introduced into an offshore structure.

Oddly enough, Table II, of the Federal Register, Title 10, Chapter 1, Part 20, Appendix B, gives allowable concentrations of radioactive materials for disposal in sewer systems. The maximum allowable concentration of Co-60 is 3×10^{-5} micro-curies/ml and the maximum allowable concentration of Ni-63 is 7 X 10^{-4} microcuries/ml. If it can be shown that the activities of the tracer used in this study will not exceed these values, it may increase the likelihood of approval.

4.3 SALVAGE VALUE OF THE STRUCTURE

Since the welds will contain radioactive isotopes for well beyond the useful life of the structure, they must be considered at least low level radioactive waste and may have to be disposed of accordingly when the platform reaches the end of its useful life (See Federal Register, Title 10, Chapter 1, Part 20 for the relevant regulations). This may result in a loss of salvage value in the portions of the platform that use this detection system. This potential loss should be taken into account when a decision to use this system is being considered.

4.4 EFFECT OF CATHODIC PROTECTION ON CORROSION IN A CRACK

Since offshore steel structures are generally cathodically protected, the effects of cathodic protection on the corrosion- related release of tracer from a crack must be considered. Since cathodic protection is considered incapable of stopping a propagating corrosion fatigue crack and may indeed accelerate it, it is a safe assumption that cathodic protection does not prevent corrosion inside a crack. This seems reasonable when one considers that the current required to protect the internal surfaces of a crack must exit through the surface opening of the crack, resulting in a dramatic increase in current density. If the cathodic protection causes the escaping metal ions to plate out at the surface of the structure adjacent to the crack, so much the better. Rather than diffusing through a stagnant boundary layer and eventually being washed away, the tracer will remain at the crack opening and will help give an indication when the weld is next inspected. This issue is, however, unclear and will have to be clarified by further work before this system can be realistically considered for application.

4.5 AVAILABILITY OF ISOTOPES

Because of its widespread commercial use, Co-60 is readily available, but Ni-63 does not have such a widespread commercial application, does not appear to be easily found and may be expensive if found.

4.6 Dilution of the Tracer

It is expected that the tracer will be diluted when it exits the crack. However, the ubiqitous marine growth will keep it from being immediately washed away by the current and will require that the tracer diffuse through a stagnant boundary layer. Diffusion through this boundary layer has been modelled with a numerical analysis method as a part of this study. The results are shown in Fig. 5 and the modelling process is described in Appendix B.

4.7 SENSITIVITY TO COMMON MODES OF FAILURE

The proposed detection system is only capable of detecting cracks that propagate through the weld metal itself. Corrosion fatigue in offshore platforms commonly initiates at the toe of a weld and propagates through the base metal. Such a crack would not, of course, be detectable with the proposed system. (See Fig. 6.)

Generally, the only time that a crack will initiate and propagate through the weld metal is when there is a significant weld defect that sharply reduces the integrity of the weld metal. This serves, of course, to further emphasize the need for rigorous quality control during welding. Indeed, one author goes so far as to say that,

> "Most cracks in welding and other structural defects discovered during later surveys had occurred during construction and were detectable at that time.(64)"

4.8 NOISE FROM OTHER SOURCES OF TRACERS

There are no natural sources of Co-60 or Ni-63. Co-60 is produced artificially and released into the oceans by

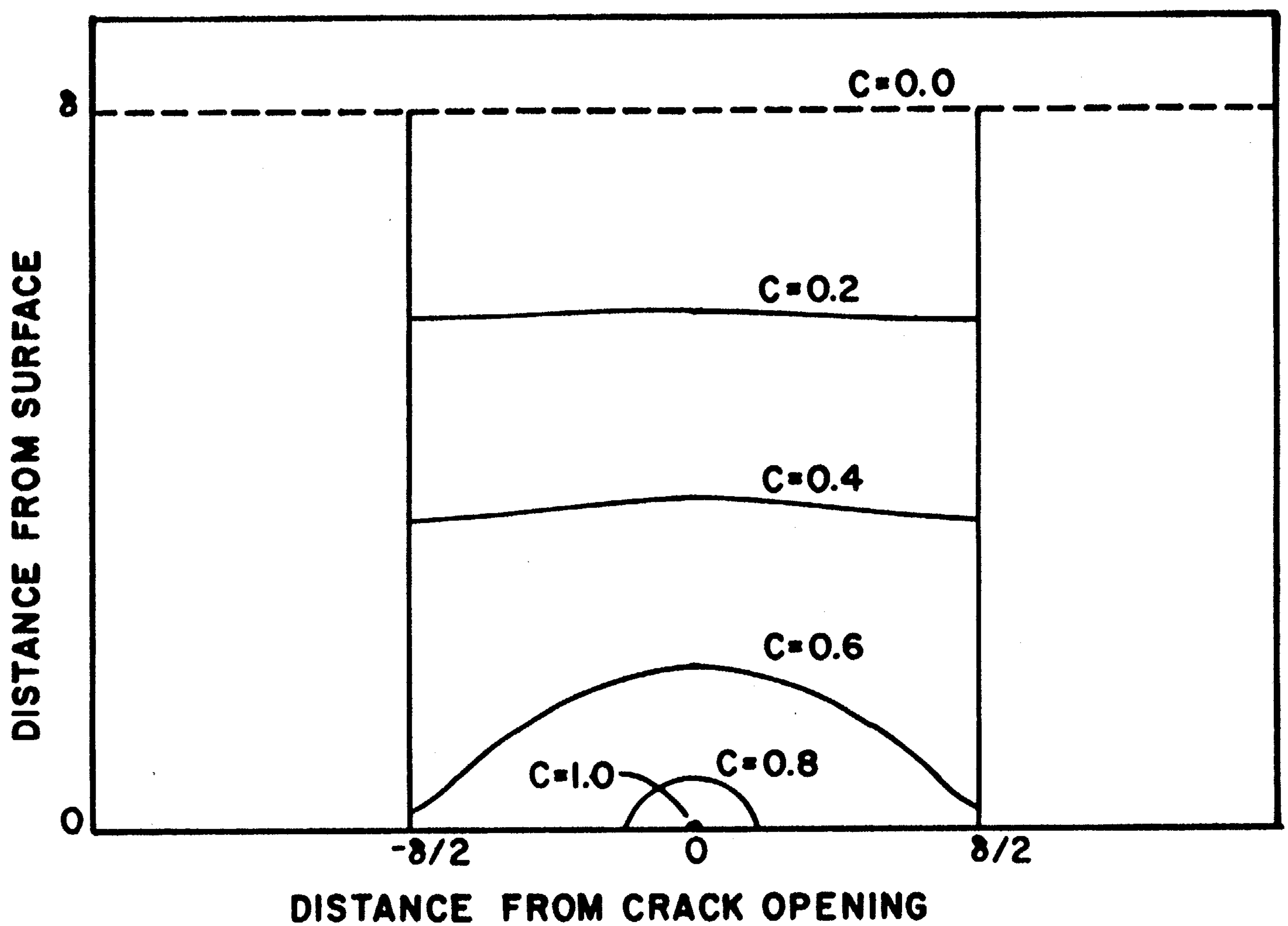

FIGURE 6: CONCENTRATION MAP FOR DIFFUSION OF A TRACER INTO A STAGNANT BOUNDARY REGION

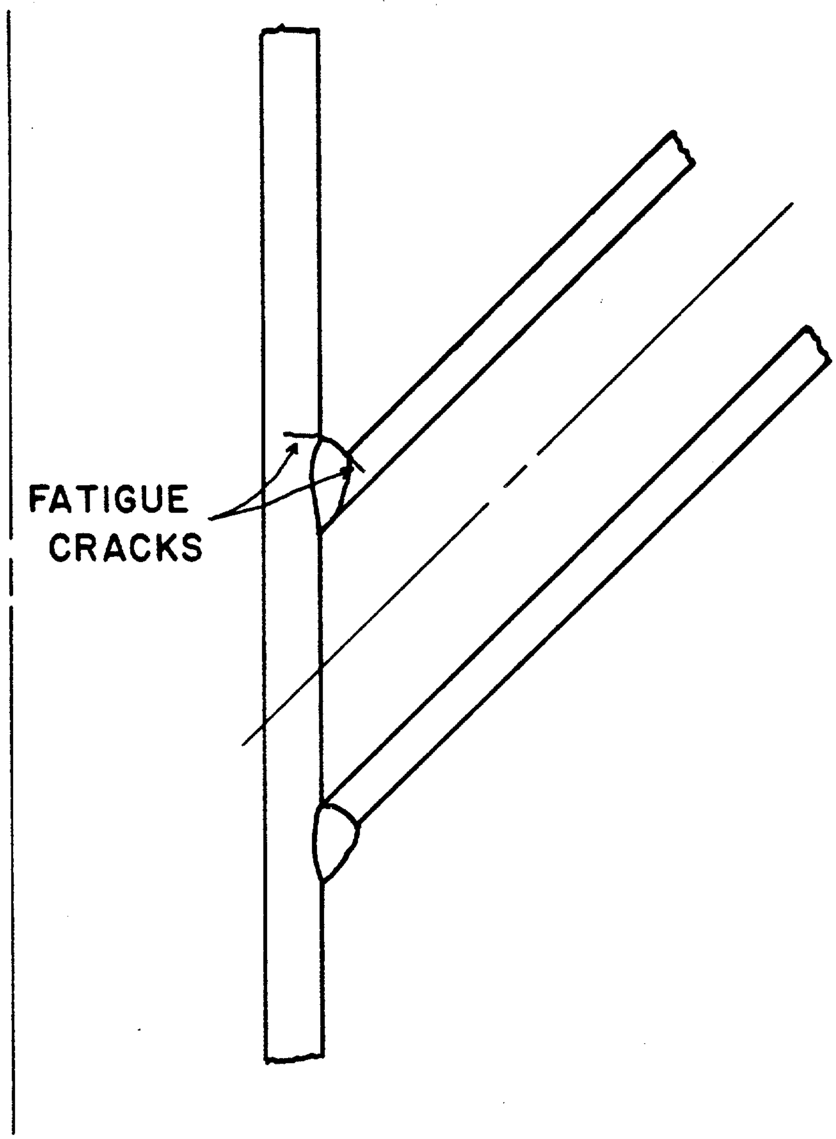

FIGURE 7: SCHEMATIC SECTION OF TUBULAR JOINT SHOWING TYPICAL LOCATION OF FATIGUE CRACKS

nuclear reactors, nuclear submarines, oceanic disposal of radioactive wastes, and nuclear powered ships. The production of Co-60 from these sources is expected to decrease as alloys containg cobalt are being eliminated from nuclear reactors(55).

CONCLUSIONS

1. It appears that it is possible to detect cracks in the weld metal of structural steel welds in seawater by including a tracer only in the interior passes of a weldment and analyzing the adjacent seawater for that tracer.

2. Both Co-60 and Ni-63 appear to be acceptable radioactive tracers for this process, although provisions for the containment of gamma radiation must be taken when Co-60 is used.

3. An in-situ irradiation process where non-radioactive isotopes of cobalt or nickel are used during welding and transformed to the desired radioactive isotopes by a portable neutron source after welding appears feasible.

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APPENDIX B

Modelling of Diffusion through Stagnant Boundary Layer

1.0 INTRODUCTION

Since the ubiquitous marine growth on offshore oil platforms will create a stagnant boundary layer around the surface of the platform members, any tracer that is released from a crack will be forced to diffuse through that stagnant layer. This modelling was done in order to estimate the tracer distribution and average concentration of tracer in the boundary layer so that the amount of radiation impinging on a passing radiation detector could be estimated.

Assuming no mixing, diffusion of the tracer will be described by Fick's First Law,

$$(1) \qquad J_x = - D * \frac{dC}{dx}$$

and Fick's Second Law, for two dimensional flow,

$$(2) \qquad D * \frac{d^2C}{dx^2} + D * \frac{d^2C}{dy^2} = \frac{dC}{dt} .$$

For steady state or pseudo-steady state conditions,

(3) $$\frac{dC}{dt} = 0$$

and Fick's Second Law may be stated,

(4) $$\frac{d^2C}{dx^2} + \frac{d^2C}{dy^2} = 0$$

This equation was modeled numerically to describe the diffusion of the tracer through a stagnant, constrained boundary layer.

2.0 THE MODELLING PROCESS

With numerical analysis techniques, a function is decribed as a set of discrete values distributed in a matrix over the region which is to be investigated. The differential equation is approximated in a matrix form and used to generate a set of simultaneous equations which are then solved to generate a "map" of values for the function over the region.

Numerically, the second derivative of a function can be approximated by the equation,

(5) $$\left.\frac{d^2F}{dz^2}\right|_{zi} = \frac{1}{h^2}F(z_{i-1}) - 2*F(z_i) + F(z_{i+1})$$

or, in matrix form,

$$(6) \qquad \begin{matrix} 1 & -2 & 1 \end{matrix} \quad F$$

When equation (4) is expressed numerically in matrix form, it becomes,

$$(7) \qquad \begin{matrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{matrix} \quad C \quad = \quad 0,$$

This matrix is valid for all points inside the boundary layer that are not on the edge of the matrix. At the edge of the matrix, boundary conditions must be applied. The ones assumed here were that the concentration of tracer dropped immediately to zero at the outer edge of the boundary layer exposed to the ocean ($C = 0$) and the other boundaries were impermeable ($C_{i+1} = C_i$) with the exception of the crack opening, where the dimensionless concentration was set to a value of one. (The concentration of tracer everywhere in the boundary layer was expressed as a fraction of the concentration at the crack opening.). These changed equation (7) to,

$$(8) \qquad \begin{matrix} 0 & 1 \\ 1 & -3 \\ 0 & 1 \end{matrix} \quad C \quad = \quad 0$$

at the impermeable boundaries, and

$$(9) \qquad \begin{matrix} 0 & 1 \\ 1 & -4 \\ 0 & 1 \end{matrix} \quad C \quad = \quad 0$$

at the exposed edge of the boundary layer.

These equations were used to generate a set of simultaneous equations which were solved with the use of IMSL subroutines on the CSM DEC-10 computer, giving the concentration map shown in Figure 5.

3.0 USE OF THIS MODEL TO ESTIMATE REQUIRED CONCENTRATION

This model can be used to estimate the tracer content reqired in the weld metal for the final application of this process. The information required is the dimensions of the boundary layer, the diffusion coefficient of the tracer ion in seawater, the sensitivity of the detector, the depth of the crack into the tracer-laden weld passes, and the release rate of the tracer from the internal surfaces of the crack.

The concentration values generated from the model can be used to calculate an average concentration of tracer in the boundary layer as a fraction of the concentration at the crack opening. If the sensitivity of the detector can be expressed as a minimum average concentration of the radioactive tracer in the boundary layer, this can be equated to the calculated average concentration and solved for the concentration at the crack opening. This concentration at the crack opening will be the minimum concentration there such that the detector will detect radiation from released tracer. This value can be multiplied by the concentrations generated by the model to get actual concentrations and concentration gradients can be approximated by looking at the difference between adjacent values of the concentration and dividing by the distance between them. The flow of tracer out of the boundary layer can be calculated by multiplying the diffusivity of the ion (about 10^{-5}) by the concentration gradient and multiplying that product by the exposed area of the constrained boundary layer.

If one assumes steady-state or pseudo-steady-state conditions, conservation of mass requires that the amount of tracer released by the crack in any given period of time must equal the amount of tracer that diffuses out of the boundary layer. The amount of tracer that is released by the crack can be estimated from the experimental data generated in this study if one assumes that the tracer release rate is simply linearly proportional to the concentration of the tracer in the tracer-laden weld passes. The minimum concentration of tracer required in the weld passes would then be the flow out of the crack divided by this proportionality constant and the area of the crack in the tracer-laden passes.

4.0 SAMPLE CALCULATION

If one assumes the following typical values for the variables listed,

Diffusivity of tracer	= 10^{-5} cm^2/sec
Depth of boundary layer	= 2 cm
Width of boundary layer	= 2 cm
Crack penetration into tracer-laden passes	= 1 cm
Sensitivity of detector	= 0.01 ppb

and uses the following values from the computer model,

Average Concentration = 0.31 × Concentration at crack opening

$$\text{Concentration gradient at exposed surface} = \frac{0.73 \times \text{Concentration at crack opening}}{\text{Depth of boundary layer}} ,$$

and the experimental values in Table IV, one calculates,

Concentration at crack opening	= 0.032 ppb = 3.1×10^{-11} g/cm^3
Flow out of boundary layer	= 2.3×10^{-16} g/s per cm length
Minimum tracer level in weld	= 1.0 ppm Ni-63 or 0.9 ppm Co-60.

These values should not be used for design purposes because the sensitivity of the detector is a strong function of the energy of the emitted radiation and must be established experimentally, and the rate of the tracer release has not been established at these very low levels of tracer elements.